Synoptic Influences on Snowfall Event Characteristics in the Southern Appalachian Mountains

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ABSTRACT

The synoptic-scale influences on snowfall event characteristics (e.g., total snowfall, liquid equivalent, density, vertical structure, and temperature) remain a source of considerable uncertainty, particularly in mountain regions, where snowfall may result from a wide variety of circulation regimes, antecedent upstream air trajectories, and boundary layer conditions. This is especially true in the southern Appalachian Mountains, where snowfall occurs in association with Miller A and B cyclones, Alberta Clippers, Ohio Valley cyclones, and NW upslope flow in the absence of a surface cyclone or frontal feature. In this paper, we investigate characteristics of snowfall events by analyzing manual snowfall observations, meteorological characteristics (e.g., temperature, relative humidity, wind speed and direction), vertical structure of precipitation (e.g., echo top heights), and synoptic patterns for 122 snowfall events from 2006 to 2012 on Poga Mountain, North Carolina, USA. Results indicate that 87% of the observed snowfall and 74% of the liquid equivalent during the period were associated with low-level W or NW flow. The heaviest snowfall and liquid equivalent precipitation occurred with Miller A or B cyclones in association with low-level NW flow, which contributed 30% of the total snowfall and 23% of the total liquid equivalent during the study period. New snowfall density was highly variable, with the highest values associated with Miller A or B cyclones with deep isothermal layers near freezing and the lowest values associated with very cold and shallow NW upslope flow. Our results highlight the importance of multi-scale analyses of orographic snowfall, particularly in linking topography, cloud microphysics, and synoptic-scale circulation.

Keywords: synoptic influences, snowfall event characteristics, southern Appalachian Mountains

INTRODUCTION

Synoptic-scale influences on snowfall event characteristics (e.g., total snowfall, liquid equivalent, density, vertical structure, and temperature) remain a source of considerable uncertainty in mountain regions. This is particularly true in the southern Appalachian Mountains, where snowfall may result from a variety of circulation regimes (Perry et al. 2010), antecedent upstream air trajectories (Holloway 2007, Perry et al. 2007), and boundary layer conditions (Miller 2012), resulting in a significant forecasting challenge (Gaffin et al. 2003, Keighton et al. 2009)

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and complex spatial patterns (Perry and Konrad 2006, Hall et al. 2010, Sugg et al. 2012). Snowfall impacts can be substantial, with 265 cm mean annual snowfall totals at the highest elevations (e.g., Mt. LeConte, TN; 1,979 m asl) and >100 cm falling with major storms, such as the Blizzard of 1993 and Hurricane Sandy in 2012 (Martin and Perry 2013). This paper summarizes six years of collaborative research focused on the multiscale atmospheric influences on orographic snowfall and is guided by the following research questions:

1) What is the snow climatology of Poga Mountain, NC, during the period 2006-2012?
2) How do the observed new snow properties (e.g., liquid equivalent, density, MRR echo top heights) vary according to synoptic classification?
3) What are the dominant synoptic patterns responsible for snowfall in the region from 2006 to 2012?

DATA AND METHODS

Poga Mountain, NC, located along the NC/TN border in the southern Appalachian Mountains (Fig. 1) served as the primary field site for this study. Table 1 summarizes the variables collected, location, temporal resolution, and instrumentation/source. A mountaintop meteorological station located at 1,140 m provided temperature, relative humidity, wind speed, and wind direction, whereas a second meteorological station located at 1,018 m provided liquid-equivalent precipitation from a Pluvio weighing precipitation gauge and present weather code from a Parsivel disdrometer (e.g., Löffler-Mang and Joss 2000, Löffler-Mang and Blahak 2001). Due to the inherent challenges of accurately measuring snowfall using automated instrumentation (e.g., Rasmussen et al. 2012), the first author also made manual observations of new snowfall, new snow liquid equivalent (SLE), and gauge-collected liquid equivalent precipitation at 7 am and 7 pm LST during snow events. The Poga Mountain observing site became an official Community Collaborative Rain, Hail, and Snow (CoCoRaHS) station (Flat Springs 1.2E; e.g., Cifelli et al. 2005, Doesken 2007) in 2007 and an official NWS cooperative observer (COOP) station (Flat Springs 1E) in 2010. As such, all snowfall observations followed accepted standards for both the CoCoRaHS and COOP networks, as outlined by Doesken and Judson (1996).

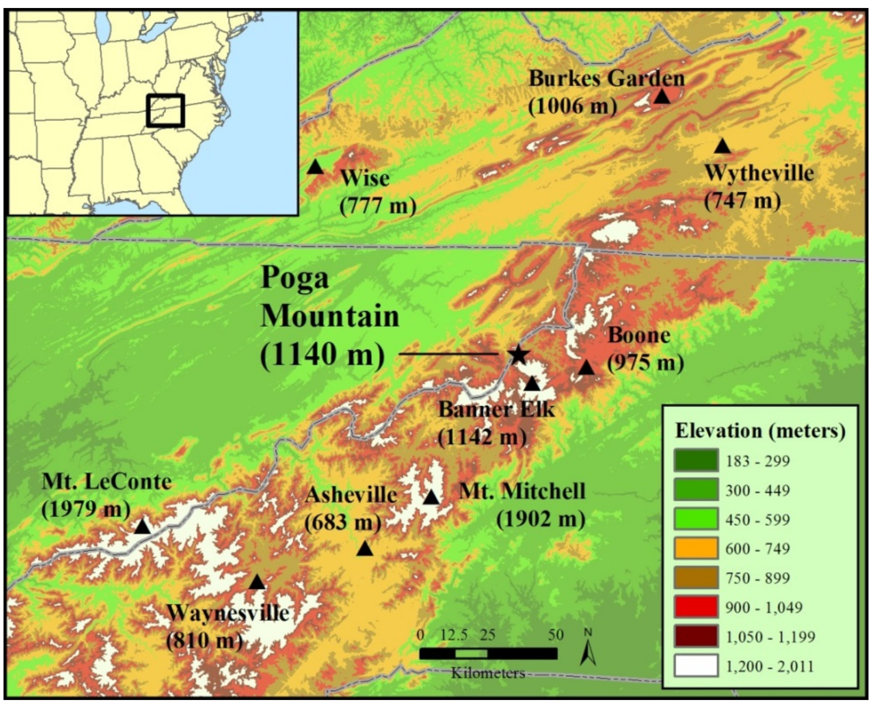

Figure 1. Location of study site and topographic setting.

Table 1. Summary of data sources.

Variable(s)	Elevation or Location	Temporal Resolution	Source
Temperature and Relative Humidity	1,140 m	1-Min	Vaisala HMP45C Probe
Wind Speed and Direction	1,140 m	1-Min	RM Young 05103 Alpine
Liquid Equivalent Precipitation	1,018 m	1-Min	Pluvio Weighing Gauge
SYNOP Present Weather Code	1,018 m	1-Min	Parsivel Disdrometer
Radar reflectivity and Doppler Velocity	1,018 m	1-Min	Micro Rain Radar (MRR)
Snow Microscopy Observations	1,018 m	1-Hr	Manual Observations
Upper Air Soundings	1,018 m	3-hr	Rawinsonde Releases
700 hPa Vertical Velocity 850 hPa Wind Speed and Direction	4 Grid Cells Nearest Poga Mt.	3-hr	North American Regional Reanalysis (NARR) Data
Composite Plots of Synoptic Fields	Eastern U.S.	3-hr	NARR Data
Surface Analyses	United States	3-hr	NOAA WPC
New Snowfall, Snow Liquid Equivalent, and Density	1,021 m	12-hr	Manual Observations
Gauge-Collected Total Precipitation	1,021 m	12-hr	Manual Observations
New Snowfall and Snow Depth	S. Appalachian Mts.	24-hr	NWS COOP and CoCoRaHS

We deployed a vertically pointing Micro Rain Radar (MRR; e.g., Peters et al. 2002, Yuter and Houze 2003) on Poga Mountain from October 2006 to May 2009, which provided continuous profiles of hydrometeor reflectivity (dBZ) and Doppler velocity from the surface (1,018 m asl) to 5,500 m asl. MRR data were also used to identify melting layer height in mixed precipitation events (Yuter et al. 2008), classify precipitation as scattered vs. continuous, and analyze the vertical structure and associated echo top heights. Upper air soundings and snow microscopy observations were also made during planned Intensive Observation Periods (IOPs) in the 2007-08, 2008-09, and 2009-10 snow seasons. Snow events were identified following the methodology of Perry et al. (2007, 2010, 2013) and using all available observations, including MRR, Pluvio, Parsivel, and manual. The beginning of each event was defined as the hour measurable snowfall was first observed, event maturation as the hour of heaviest snowfall, and event ending as the hour measurable snowfall was last observed. An event remained active as long as measurable snowfall was reported during a 6-hr period; breaks over 6 hrs resulted in the identification of separate snowfall events.

Table 2. Synoptic classification scheme used in this study (modified after Perry et al. 2010).

Class	Description
NE	Northeastward tracking low passes to the north of area
SE	Southeastward tracking clipper passes north or across the area
M	Miller A/B cyclones originating in the Gulf of Mexico
CL	Cutoff Low -- A 500 hPa cutoff low moves across the region (often slow & sometimes quasi-stationary).
LC	Lee Cyclogenesis -- Surface lows develops to the lee of the Appalachian Mountains
U	Upslope -- W/NW upslope flow in the absence of synoptic-scale surface features
Non-U	Non-NW flow events
X	Unclassified -- Does not fit any of the synoptic classes
**-U*	Denotes upslope flow (250 to 360 degrees) at event maturation for any of the synoptic classes

The synoptic-scale circulation associated with each snow event was classified according to a modified version (Table 2) of the Perry et al. (2010) manual scheme developed for an analysis of snowfall events in the Great Smoky Mountain region of the southern Appalachian Mountains. The modified classification scheme is hybrid in nature, with part of the classification performed manually through analysis of surface and upper-air charts and all available observations (including radar) and the other part performed in an automated fashion according to wind direction at event maturation. We manually classified snow events several times per snow season, first individually, and, when differences were noted during scheduled teleconferences, the events were discussed in detail until we came to a consensus. The dominant storm tracks represented in this modified classification scheme, as defined by average surface low pressure positions, are further illustrated in Figure 2. Composite synoptic plots of mean sea-level pressure, 700 hPa vertical velocity, 500 hPa vector wind, and 850 hPa vector wind were created from the North American Regional Reanalysis (NARR) data using the online interface (NOAA ESRL 2012) for the three heaviest classes: SE-U, M-U, and Non-U.

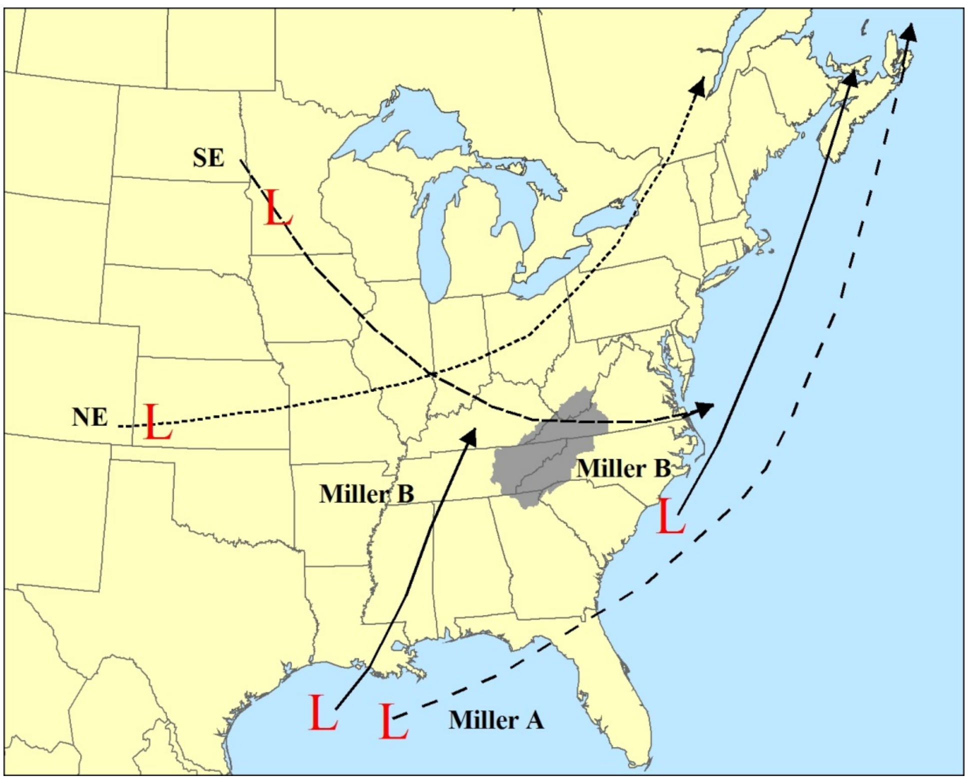

Figure 2. Primary surface low pressure tracks influencing the southern Appalachian Mountains (shaded).

RESULTS AND DISCUSSION

Snow Climatology

Table 3 summarizes the observed snowfall statistics on Poga Mountain for the period 2006-2012. Mean annual snowfall was 138.6 cm (99.1 mm SLE), with a minimum of 62 cm (43.7 mm SLE) in 2007-08 and maximums of 230 cm (165.1 mm SLE) in 2009-10 and 248 cm (168.4 mm SLE) in 2010-11. The anomalously high snowfall totals in the 2009-10 and 2010-11 snow seasons were in association with extreme negative phases of the Arctic Oscillation (e.g., Cohen et al. 2010), with daily AO index values reaching as low as -5.2 standard deviations in February and December 2010. New snowfall density averaged 74 kg m^{-3}, and the site averaged 20.3 snow events per year. Although considerable inter-annual variability of snowfall totals is evident on Poga Mountain and across the region (Table 4), the 6-yr mean annual snowfall observed at long-term COOP stations in the region was very close to the respective 30-yr climatological means (1981-2010 base period). Only two stations, Banner Elk and Asheville, had 6-yr mean annual snowfall for the period 2006-2012 that deviated more than 10% from the 30-yr mean annual snowfall. Therefore, we believe that the 6-yr study period is generally representative of the snow climate in the southern Appalachian Mountains. The 138.6 cm mean annual snowfall at Poga Mountain makes it comparable to Burkes Garden and Wise, VA, but considerably below the 264.7 cm mean annual snowfall on Mt. LeConte, TN.

Table 3. Poga Mountain, NC, snowfall summary, 2006-2012.

Year	Snowfall (cm)	Snow Liquid Equiv. (mm)	Snow Density (kg m^{-3})	Snow to Liquid Ratio	Number of Snowfall Events	Mean Snowfall per Event (cm)
2006-07	87.1	67.1	77	13.0	20	4.4
2007-08	62.0	43.7	70	14.2	23	2.7
2008-09	138.4	94.0	68	14.7	18	7.7
2009-10	230.1	165.1	72	13.9	23	10.0
2010-11	248.2	168.4	68	14.7	23	10.8
2011-12	65.5	56.1	86	11.7	15	4.4
Mean	*138.6*	*99.1*	*73*	*13.7*	*20.3*	*6.7*

The majority of the snowfall events (88%) observed on Poga Mountain during the study period occurred in association with low-level (e.g., 1,140 m asl or ~880 hPa) W/NW flow, with the remaining events associated with E/SE flow primarily (Fig. 3). This finding confirms the dominance of northwest flow snowfall (NWFS; e.g., Perry et al. 2007, Keighton et al. 2009) to the snow climatology of the higher elevation windward slopes during periods of W/NW low-level flow. In fact, the percentage of total snowfall events tied to W/NW flow on Poga Mountain is considerably higher than previous studies (e.g., Perry et al. 2006) have reported for selected COOP stations in the region. The moist layer and associated hydrometeor echo top heights for the W/NW flow snow events are also typically quite shallow, with echo top heights < 3.0 km asl (Fig. 4) for a sample of events observed using the vertically pointing MRR. A few of the events were even characterized by echo top heights of < 1.5 km asl, which is < 500 m higher than the observing site on Poga Mountain, located at 1,018 m. In contrast, 83% of the E/SE flow snow events were associated with much deeper moisture, with echo tops > 3.5 km asl.

Table 4. Mean annual snowfall (1981-2010) for selected cooperative observer (COOP) stations and percent of normal snowfall during the study period (2006-2012).

Station	1981-2010 Mean Annual Snowfall (cm)	1981-2010 Coefficient of Variation	Percent of Normal 2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	*2006-12*
Asheville, NC	33.6	0.67	25%	54%	57%	260%	209%	6%	102%
Banner Elk, NC	101.2	0.50	79%	45%	108%	228%	151%	44%	109%
Boone, NC	89.5	0.55	43%	28%	67%	171%	139%	35%	81%
Mt. Mitchell, NC	229.6	0.42	34%	50%	92%	186%	151%	56%	95%
Waynesville, NC	35.1	0.64	29%	28%	67%	226%	149%	14%	85%
Mt. LeConte, TN	264.7	0.38	51%	83%	91%	146%	155%	35%	93%
Burkes Garden, VA	133.8	0.34	78%	66%	96%	116%	93%	51%	83%
Wise, VA	134.2	0.42	51%	55%	92%	151%	156%	N/A	101%
Wytheville, VA	51.2	0.73	37%	29%	66%	242%	109%	52%	89%

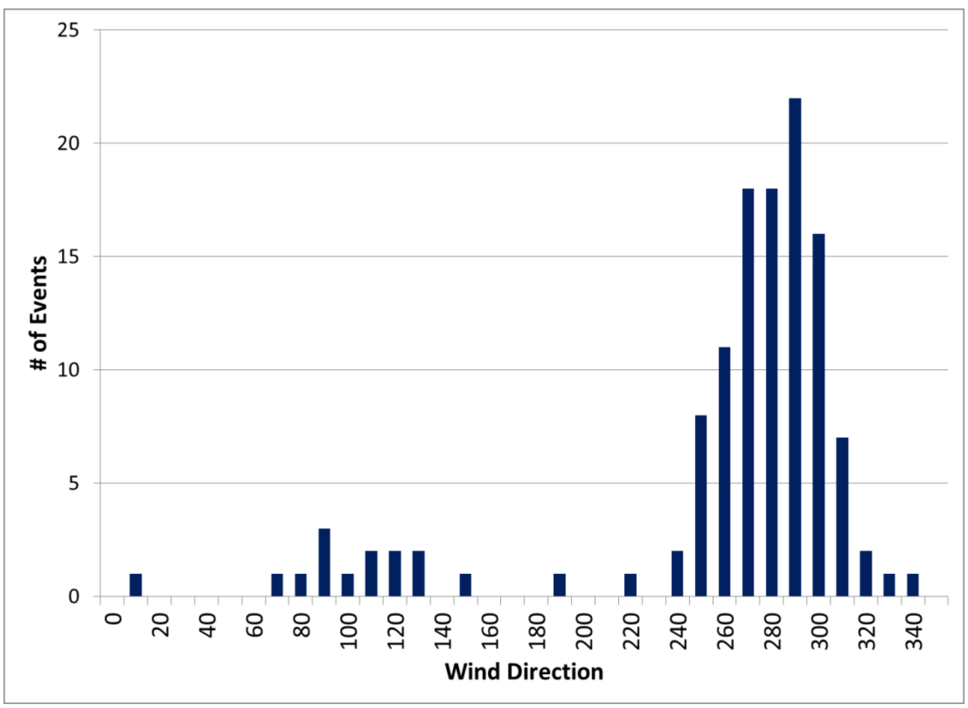

Figure 3. Wind direction at event maturation for all snow events (n=122) on Poga Mountain, NC, 2006-2012.

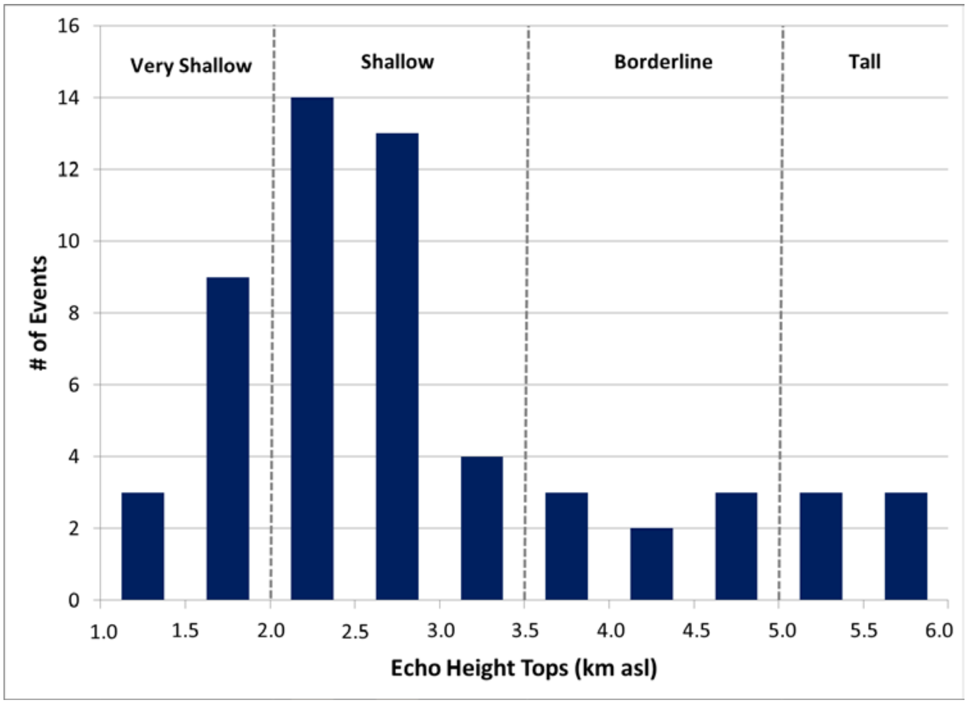

Figure 4. MRR echo top heights at event maturation for all snow events (n=57) on Poga Mountain, 2006-2009.

Snowfall Event Characteristics According to Synoptic Class

Table 5 summarizes the snowfall event characteristics on Poga Mountain according to synoptic class. Upslope (U) events were the most common, representing 25% of the total events during the period, but were typically light, with mean event snowfall of 4.1 cm (2.3 mm SLE) and therefore contributed only 14% (12%) of the snowfall (SLE). The Miller A/B cyclones with W/NW flow (M-U) represented 16% of the total events, but 30% (23%) of the total snowfall (SLE). The northeastward-tracking cyclones with W/NW flow (NE-U) events also represented 16% of the total events, but only 9% of total snowfall and SLE. Non-U events, or those with wind directions at event maturation ranging from 14 to 195 degrees, occurred 13% of the time, consisting of 15% (26%) of the total snowfall (SLE). As the surface low tracked off to the northeast, winds typically shifted and produced lingering light snow accumulations in association with NW flow. The southeastward-tracking clippers with W/NW flow (SE-U) occurred 11% of the time, representing 17% (14%) of the total snowfall (SLE). Unclassified events, or those that did not fit one of the classes in the synoptic classification scheme, with W/NW flow (X-U), occurred 11% of the time and represented 9% of the total snowfall and SLE. The 500 hPa cutoff lows (CL-U) and lee cyclones (LC-U) were relatively infrequent during the study period, occurring 3% and 6% of the time, respectively.

New snowfall density was relatively low for those classes with W/NW flow at event maturation, with values ranging from 54 to 67 kg m^{-3} for the NE-U, SE-U, M-U, U, and X-U classes. The CL-U and LC-U classes were somewhat higher, at 76 and 89 kg m^{-3}. The Non-U class displayed the highest new snowfall density, averaging 115 kg m^{-3}. Average temperatures at 1,140 m asl on top of Poga Mountain for all classes at event maturation ranged from a low of -5.1 °C for the U events to a high of -0.7 °C for the CL-U events. The 700 hPa vertical velocity values are all positive (in units of Pa s^{-1}) for each of the synoptic classes with W/NW flow, indicating synoptic-scale subsidence and highlighting the importance of orographic lifting and other factors such as mesoscale instabilities, boundary layer structure, and boundary layer processes. The events in the Non-U class, however, are characterized by weak synoptic-scale ascent, often associated with isentropic lifting and cold-air damming (e.g., Bell and Bosart 1988).

Table 5. Snowfall event characteristics on Poga Mountain, NC, 2006-2012, according to synoptic class.

Synoptic Class	Percent of Events	Percent of Snowfall	Percent of SLE	Duration (Hrs)	Snowfall (cm)	Snow Liq. Equiv. (mm)	Snow-to-Liquid Ratio	Snow Density (kg m^{-3})	Wind Speed (m s^{-1})	Wind Direction (Degrees)	Temperature (°C)	700 hPa Vertical Velocity (Pa s^{-1})
NE-U	16%	9%	9%	14	4.6	2.7	17	59	3.9	283	-2.4	0.30
SE-U	11%	17%	14%	20	11.7	6.3	19	54	3.5	276	-2.9	0.32
M-U	16%	30%	23%	27	13.0	7.2	18	55	4.4	285	-4.5	0.23
CL-U	3%	2%	3%	13	5.1	3.9	13	76	2.1	281	-0.7	0.71
LC-U	6%	4%	5%	12	4.6	4.2	11	89	3.7	299	-4.3	0.53
U	25%	14%	12%	14	4.1	2.3	18	56	3.6	294	-5.1	0.37
Non-U	13%	15%	26%	17	8.4	9.7	9	115	2.7	122	-3.7	-0.20
X-U	11%	9%	9%	14	6.1	4.1	15	67	2.7	284	-2.7	0.30

An analysis of MRR echo top heights for the period 2006-2009 (Table 6), when sorted according to synoptic class, indicates that the classes with W/NW flow at event maturation typically have the lowest echo top heights. In particular, 89% of the events in the NE-U class, 67% in the M-U class, 50% in the LC-U class, 94% in the U class, and 89% in the X-U class are characterized by very shallow or shallow echo top heights. Although the majority of the events in the M-U class are very shallow or shallow, 33% are classified as tall, with echo tops > 5.0 km asl. In these events, the storm track resulted in abundant synoptic-scale ascent coincident with NW flow and a middle and lower troposphere cold enough for snow. A high percentage of the events in the SE-U class (57%) are characterized by borderline echo top heights (3.5 to 5.0 km asl), indicating the presence of a deeper moist layer in association with some of the heavier events. 50% of the Non-U events are characterized by tall echo top heights, indicating the presence of deep moisture and abundant lift.

Table 6. MRR echo top heights on Poga Mountain, NC, 2006-2009, according to synoptic class.

Synoptic Class	Very Shallow (< 2.0 km asl)	Shallow (2.0 - 3.5 km asl)	Borderline (3.5 - 5.0 km asl)	Tall (> 5.0 km asl)
NE-U	11%	78%	11%	0%
SE-U	0%	43%	57%	0%
M-U	17%	50%	0%	33%
CL-U	0%	0%	0%	0%
LC-U	25%	25%	50%	0%
U	13%	81%	6%	0%
Non-U	17%	0%	33%	50%
X-U	33%	56%	0%	11%

Composite Synoptic Plots

We created composite synoptic plots using the NARR fields (e.g., 3-hourly) closest to event maturation for the three synoptic classes contributing the most to mean annual snowfall on Poga Mt. during the period: SE-U, M-U, and Non-U. The composite plots of mean-sea level pressure (MSLP) and 700 hPa vertical velocity (Fig. 5) for the SE-U events indicate the presence of a well-defined surface cyclone over the Canadian Maritimes, with cyclonic flow dominating the eastern U.S. and favoring the propagation of southeastward-tracking disturbances from southern Canada towards the Appalachian Mountains and mid-Atlantic region. For the M-U events, the surface cyclone and associated synoptic-scale ascent is located off the mid-Atlantic coast, with strong high pressure to the west over the Great Plains, resulting in a stronger gradient over the southern Appalachian Mountains and thus enhanced upslope flow. This pattern is quite similar to the composite plot from Kocin and Uccellini (2004a, 2004b) for their T+12 cases of major snowstorms impacting the northeastern U.S. The Non-U events are characterized by a surface cyclone over the southeastern U.S. and a clear pattern of cold-air damming (CAD) along the eastern slopes of the southern Appalachian Mountains. Synoptic-scale ascent is likewise evident across the entire region.

The vector wind composite plots (Fig. 6) indicate a wind speed maximum extending from Iowa to the southern Appalachian Mountains at 500 hPa, with NW flow also dominating at 850 hPa. Although the 500 hPa trough axis is directly overhead the study area for the M-U events, the wind speed maximum is located downstream of the trough axis over the coastal areas of the southeastern U.S. The 850 hPa vector wind composite plot for the M-U events also indicates a possible Great Lakes connection. In the Non-U events, a broad 500 hPa trough axis is located over the Mississippi River Valley, with a generally weaker SW flow over the study area. The 850 hPa vector wind composite plot is consistent with the in-situ wind observations from Poga Mt., indicating SE low-level flow.

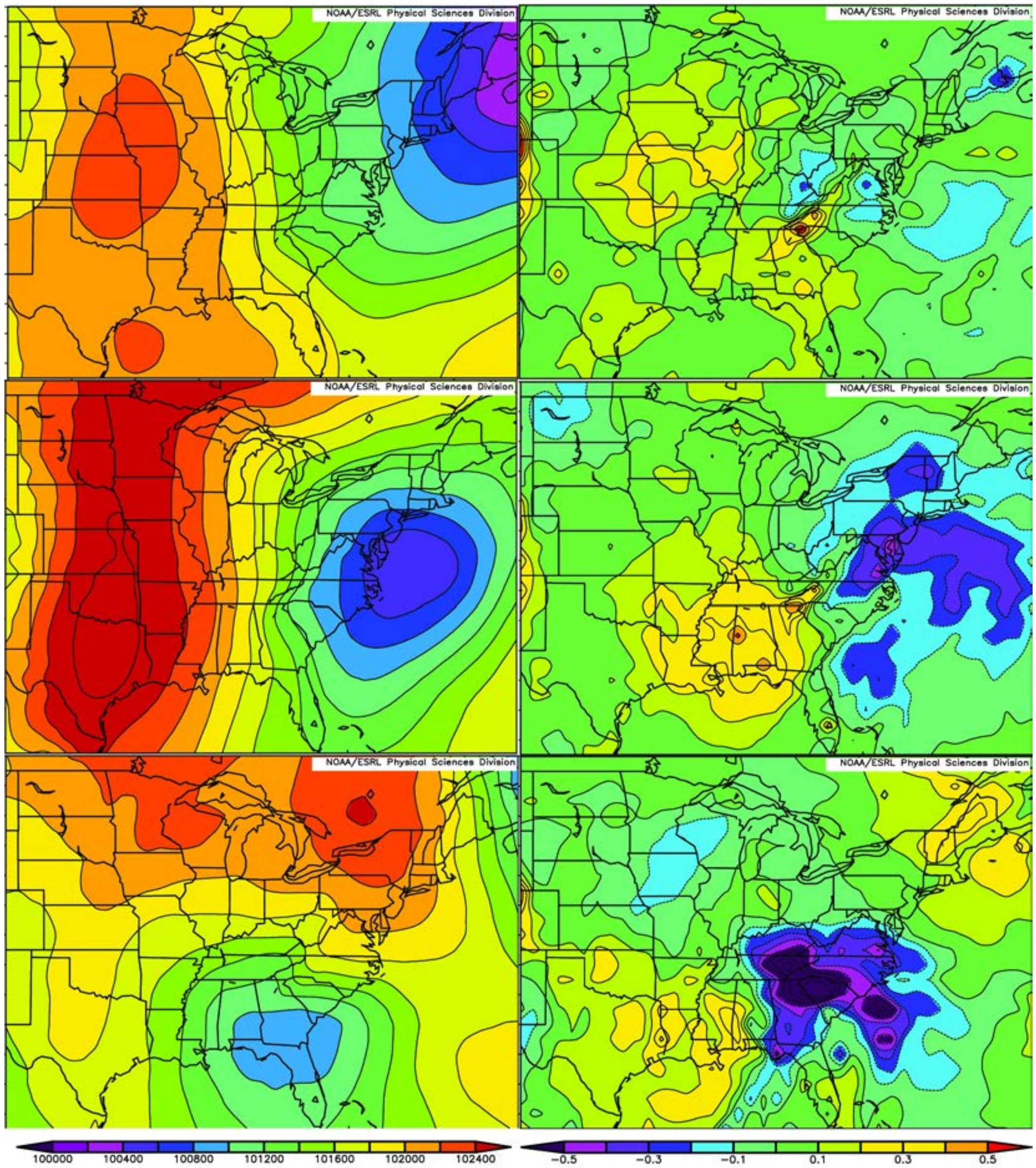

Figure 5. NARR composite synoptic plots of mean sea-level pressure (left) and 700 hPa vertical velocity (right) for SE-U (top, n=13), M-U (middle, n=19), and Non-U (bottom, n=13) events. Units are Pa and Pa s^{-1}.

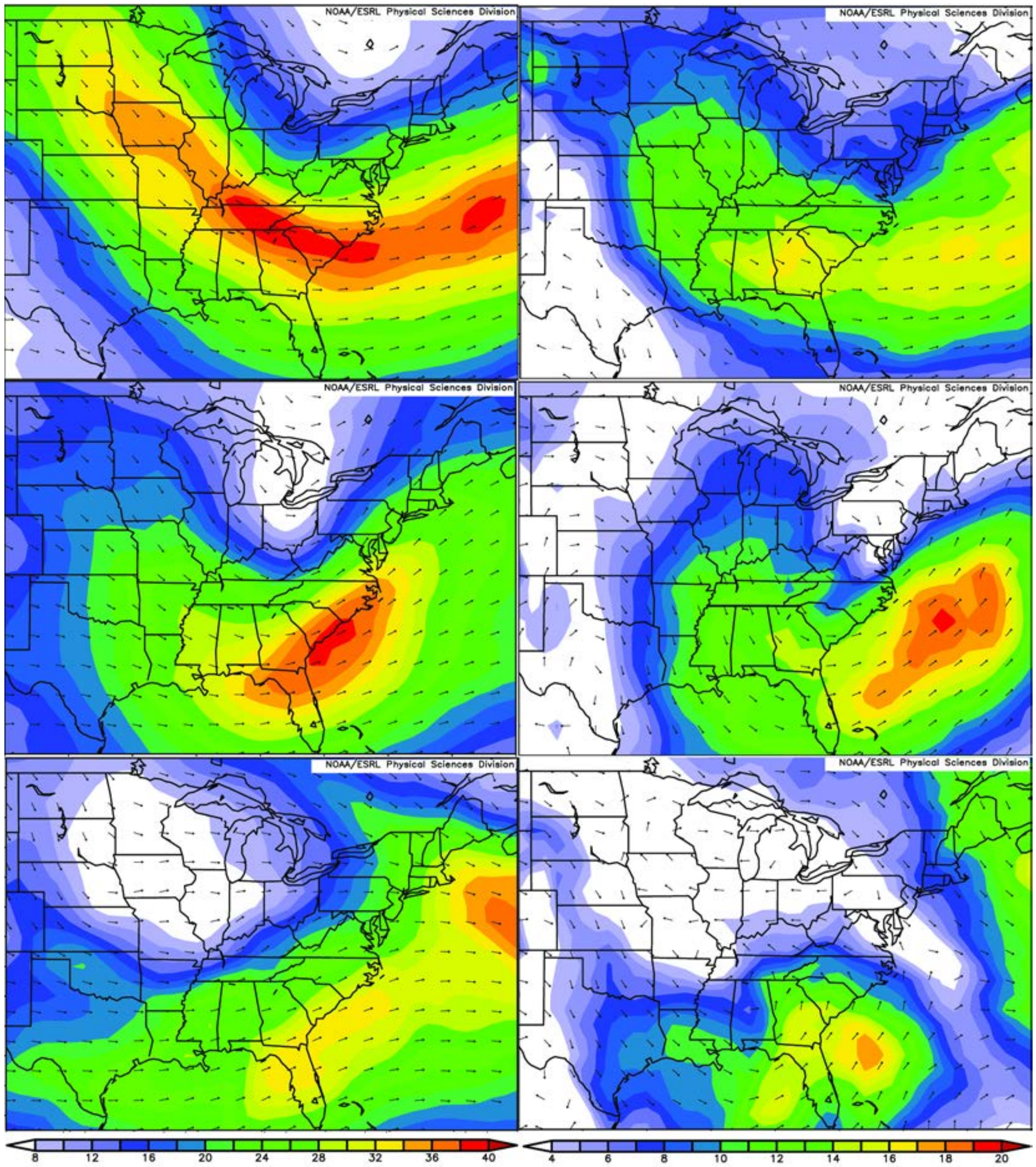

Figure 6. NARR composite synoptic plots of 500 hPa vector wind (left) and 850 hPa vector wind (right) for SE-U (top, n=13), M-U (middle, n=19), and Non-U (bottom, n=13). Units are m s^{-1}.

Case Studies

The event characteristics for six case studies representing different synoptic classes are summarized in Table 7. With the exception of the 1-2 December 2008 NE-U and 7 April 2007 LC-U event, all of the events were relatively high impact, with durations > 24 hours and snowfall totals > 20 cm. The 18-20 December 2009 Non-U Miller AB event was particularly significant, with 38.9 cm (48.3 mm) of snow (SLE). New snowfall density was highest for the 18-20 December 2009 Non-U event, consistent with the higher observed mean values for that synoptic class, whereas the deep moisture, strong synoptic-scale ascent, and relatively high surface temperatures resulted in higher new snowfall density for the 1-2 March 2009 M-U event than is typically the case. The lowest new snowfall densities, 44 and 47 kg m^{-3}, were associated with the 18-21 January 2009 SE-U and the 26-28 February 2008 U events, respectively. The analyzed NCEP surface charts at event maturation illustrate important features highlighted previously, including storm track and frontal positions, associated with the case studies (Fig. 7).

Table 7. Event characteristics for case studies.

Date of Event	Synoptic Class	Duration (hrs)	New Snow (cm)	SWE (mm)	Density (kg m^{-3})	Snow to Liquid Ratio	Temperature (°C)	Relative Humidity (%)	Wind Speed ($m\ s^{-1}$)	Wind Direction (Degrees)	700 hPa Vertical Velocity (Pa s^{-1})
1-2 Dec 2008	*NE-U*	18	7.4	3.8	52	19.3	-1.3	90.3	3.9	256	0.05
18-21 Jan 2009	*SE-U*	55	20.6	9.0	44	22.8	-3.6	94.8	2.9	298	0.08
1-2 Mar 2009	*M-U*	25	28.2	23.9	85	11.8	-1.5	96.7	5.3	348	-0.73
6-7 Apr 2007	*LC-U*	18	14.7	8.1	54	18.4	-7.5	90.6	4.8	315	0.50
18-20 Dec 2009	*Non-U*	58	38.9	48.3	124	8.1	-3.7	94.4	4.8	100	-0.25
26-28 Feb 2008	*U*	44	21.1	9.9	47	21.3	-7.2	91.4	5.3	295	0.34

Time-height plots of radar reflectivity from the MRR were also available for five of the six events (Fig. 8) and special upper air soundings for three of the events (Fig. 9), which further highlight the variability in echo top heights, character, and evolution of the snowfall events. The 1-2 December 2008 NE-U event was characterized by fairly intense, but short-lived and scattered echoes extending up to 3.5 km asl. Even with the deep moisture (Fig. 9a) echo top heights were a bit lower for the 18-21 January 2009 SE-U event – up to 3.0 km asl at event maturation and lowering to < 2.0 km asl by the end of the event. The 1-2 March 2009 is a great example of NNW upslope flow coinciding with deep moisture and strong synoptic-scale support to generate an ~ 8-hr period of moderate to heavy snowfall. In fact, the snow fell heavily in the form of extremely large aggregates between 1700 and 2000 UTC 1 March 2009, with hourly snowfall (SLE) rates of 5 cm hr^{-1} (2.5 mm hr^{-1}). A brief break in the snowfall occurred between 0600 and 0700 UTC 2 March 2009 as the main synoptic forcing and deeper moisture began to track off to the NE, but light snow continued in the very shallow NW upslope flow between 0700 and 1500 UTC 2 March 2009. The 6-7 April 2007 LC-U event was associated with several hours of virga at the beginning of the event between 1800 and 2200 UTC 6 April 2007, with moderate snow beginning at 0000 UTC 7 April 2007. Even with the weak lee cyclogenesis, echo tops remained < 3.5 km asl throughout the event. The Non-U Miller AB event or 18-20 December 2009 (no MRR image available) produced the 4th highest event snowfall total and the highest SLE during the six-year study period. The upper-air sounding at event maturation (Fig. 9b) indicates a warm nose at ~775 hPa in association with isentropic lift in southerly flow. A relatively deep isothermal moist layer exists between -5 and 0 °C, resulting in high mixing ratios for such low surface temperatures.

Lastly, the 26-28 February 2008 U event is characteristic of a classic NW flow upslope snow event with very shallow moisture in association with synoptic-scale subsidence. Echo top heights remain generally < 2.5 km asl the entirety of event, and echoes display both continuous and scattered characteristics. Although snowfall intensities were never particularly high, the long duration and persistence of the event allowed for 21.1 cm of snow to fall.

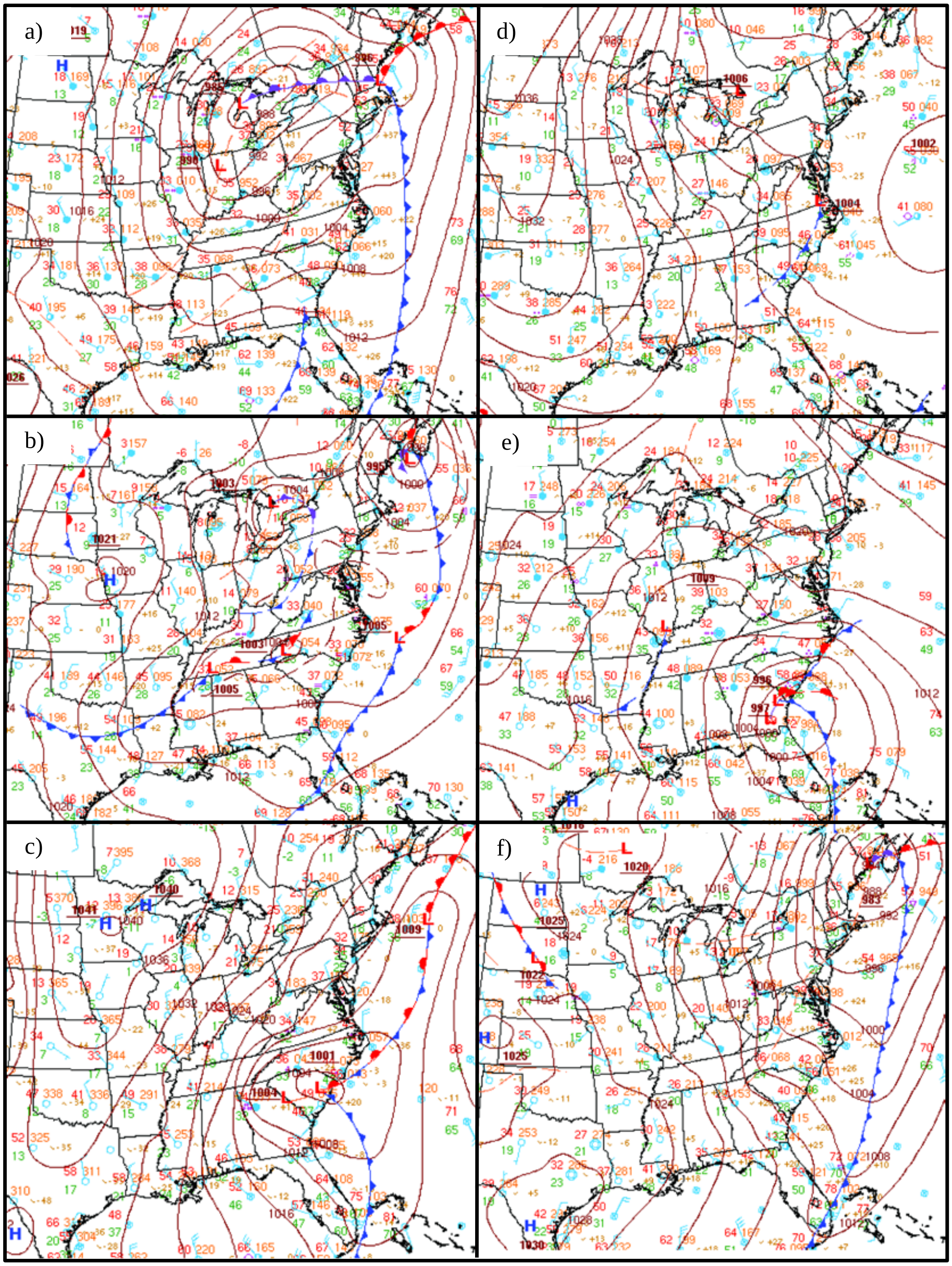

Figure 7. NCEP surface analyses at event maturation for a) 1200 UTC 1 December 2008 NE-U, b) 1200 UTC 19 January 2009 SE-U, c) 2100 UTC 1 March 2009 M-U, d) 0600 UTC 7 April 2007 SE-U, e) 0000 UTC 19 December 2009 Non-U, f) 1200 UTC 27 February 2008 U.

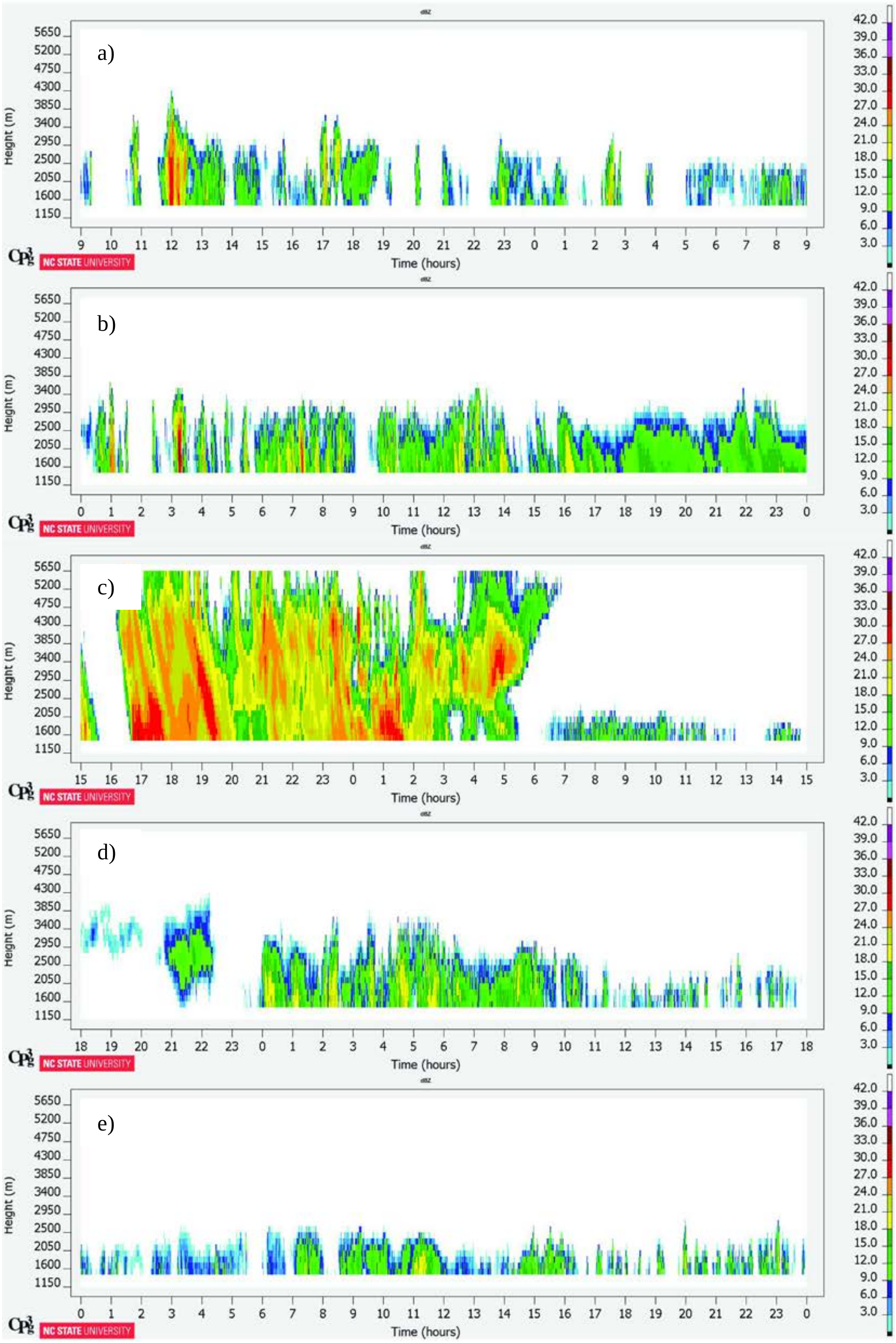

Figure 8. MRR 24-hr summaries of reflectivity (dBZ) for a) 1-2 December 2008 NE-U, b) 19 January 2009 SE-U, c) 1-2 March M-U, d) 6-7 April 2007 LC-U, and e) 27 February 2008 U.

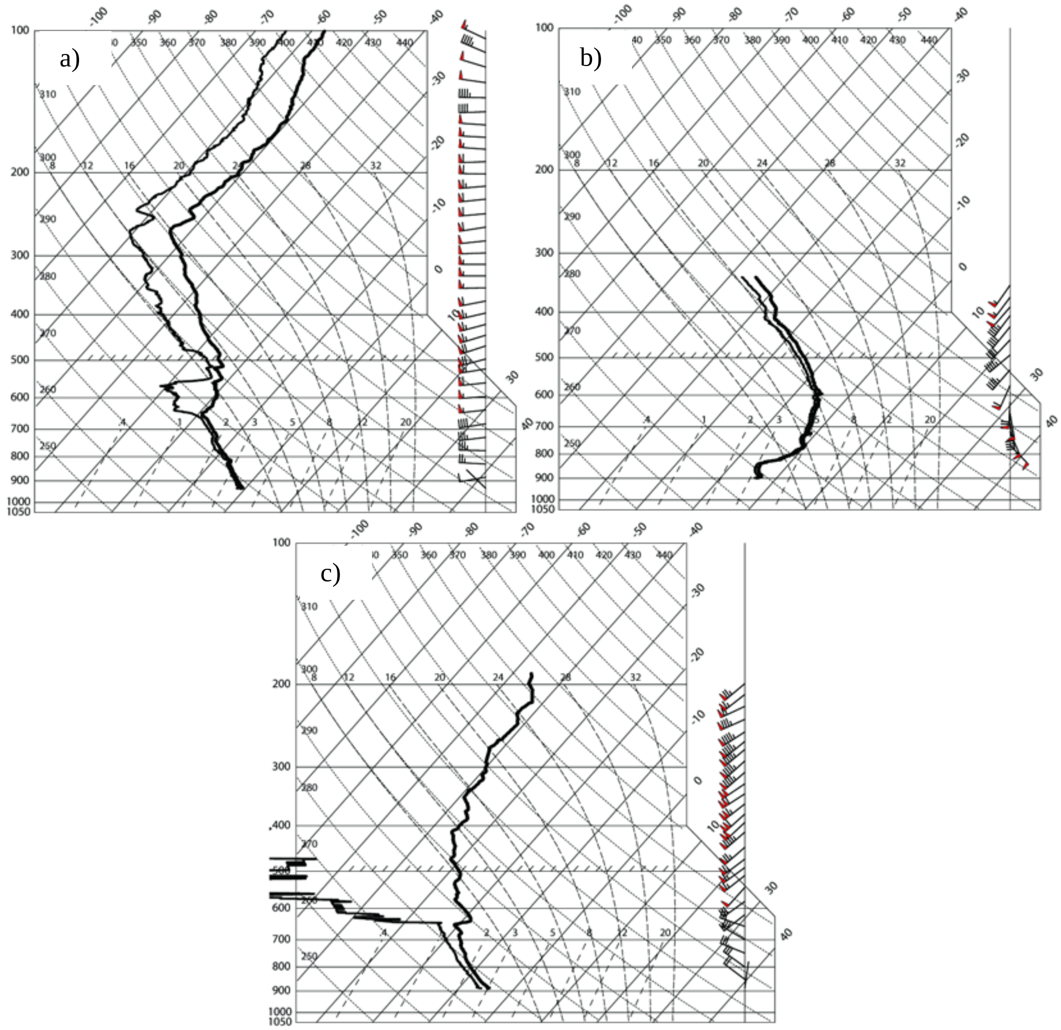

Figure 9. Skew-T plots at event maturation during special soundings for (a) 1100 UTC 19 January 2009 SE-U, (b) 0000 UTC 19 December 2009 Non-U, and (c) 1000 UTC 27 February 2008 U events on Poga Mountain, NC.

SUMMARY AND CONCLUSIONS

Mean annual snowfall (SLE) on Poga Mountain, NC, during the period 2006-2012 averaged 138.6 cm (99.1 mm), with a mean snowfall density of 73 kg m^{-3}. Although a variety of synoptic-scale circulation regimes contributed to the observed snowfall totals, 88% of the snowfall events and 74% of the total SLE are associated with W/NW flow at event maturation, confirming the dominant role of W/NW flow snowfall along favored locations of the southern Appalachian Mountains. Of the synoptic classes, the U events were the most common, although the Non-U and M-U events contributed the greatest SLE. The Non-U events were typically associated with E/SE flow and exhibited the highest new snowfall densities. Therefore, one of our principal conclusions is that low-level wind direction (W/NW vs. E/SE) is more important than the exact synoptic evolution of events. Observations from a vertically pointing MRR indicate that most W/NW flow snow events were shallow, with echo top heights < 3.5 km asl. This was particularly the case with the U events, with 94% exhibiting echo top heights < 3.5 km asl. Composite synoptic plots confirm very different storm tracks and circulation regimes between the SE-U/M-U and the Non-

U events. The SE-U and M-U events are characterized by weak or neutral synoptic-scale ascent enhanced by W/NW upslope flow, whereas the Non-U events exhibit deep moisture, abundant synoptic-scale ascent, and E/SE flow. Five case studies further illustrate the variability of snowfall event characteristics according to synoptic class, with the 26-28 February 2008 U event indicating very shallow echo top heights.

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REFERENCES

Bell, G.D., L.F. Bosart. 1988. Appalachian Cold-Air Damming. *Monthly Weather Review* 116: 137-161.

Cifelli, R., N. Doesken, P. Kennedy, L. D. Carey, S. A. Rutledge, C. Gimmestad, T. Depue. 2005. The Community Collaborative Rain, Hail, and Snow Network: Informal education for scientists and citizens. *Bulletin of the American Meteorological Society* 86: 1069–1077.

Cohen, J., J. Foster, M. Barlow, K. Saito, J. Jones. 2010. Winter 2009-2010: A case study of an extreme Arctic Oscillation event. *Geophysical Research Letters* 37, L17707, doi:10.1029/2010GL044256.

Doesken, N.J., A. Judson. 1996. *The Snow Booklet: A Guide to the Science, Climatology, and Measurement of Snow in the United States*. Colorado Climate Center: Fort Collins, CO.

Doesken, N. 2007. Let it Rain: How one grassroots effort brought weather into America's backyards. *Weatherwise* 60: 50-55.

Gaffin, D.M., S.S. Parker, P.D. Kirkwood. 2003. An unexpectedly heavy and complex snowfall event across the southern Appalachian region. *Weather and Forecasting* 18: 224-235.

Hall, D.K., C.M. Fuhrmann, L.B. Perry, G.A. Riggs, D.A. Robinson, J.L. Foster. 2010. A comparison of satellite-derived snow maps with a focus on ephemeral snow in North Carolina. *Proceedings of the 67th Eastern Snow Conference*, 171-182.

Holloway, B. S. 2007. The role of the Great Lakes in northwest f low snowfall events in the southern Appalachian Mountains. M.S. thesis, Dept. of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 204 pp. [Available online at www.lib.ncsu.edu/theses/available/etd-110022007-181739/.]

Keighton, S., L. Lee, B. Holloway, D. Hotz, S. Zubrick, J. Hovis, G. Votaw, L.B. Perry, G. Lackmann, S. Yuter, C.E. Konrad, D. Miller, and B. Etherton. 2009. A collaborative approach to better understanding northwest flow snowfall in the southern Appalachians. *Bulletin of the American Meteorological Society* 90:979-991. doi:10.1175/2009BAMS2591.1

Kocin, P.J., and L.W. Uccellini. 2004a. *Northeast Snowstorms of the Twentieth Century. Vol 1: An Overview*. Amer. Meteor. Soc., 296 pp.

Kocin, P.J, and L.W. Uccellini. 2004b. *Northeast Snowstorms of the Twentieth Century. Vol 2: Case Studies*. Amer. Meteor. Soc., 522 pp.

Löffler-Mang, M., and J. Joss. 2000. An optical disdrometer for measuring size and velocity of hydrometeors. *Journal of Atmospheric and Oceanic Technology* 17: 130–139.

Löffler-Mang, M., and U. Blahak. 2001. Estimation of the equivalent radar reflectivity factor from measured snow size spectra. *Journal of Applied Meteorology* 40: 843–849.

Martin, D., L.B. Perry. 2013. Snowfall event characteristics from a high elevation site in the southern Appalachian Mountains. *Proceedings of the 70th Eastern Snow Conference*, in press.

Miller, D.K.. 2012. Near-term effects of the lower atmosphere in simulated northwest flow snowfall forced over the Southern Appalachians. *Weather and Forecasting* 27: 1198-1216. doi: 10.1175/WAF-D-11-00103.1

NOAA ESRL. 2012. 3-Hourly NCEP North American Regional Reanalysis (NARR) Composites. http://www.esrl.noaa.gov/psd/cgi-bin/data/narr/plothour.pl

Perry, L.B, C.E. Konrad. 2006. Relationships between NW flow snowfall and topography in the southern Appalachians, USA. *Climate Research* 32: 35-47.

Perry, L.B, C.E. Konrad, T.W. Schmidlin. 2007. Antecedent upstream air trajectories associated with northwest flow snowfall in the southern Appalachians, USA. *Weather and Forecasting* 22: 334-352.

Perry, L.B., C.E. Konrad, D. G. Hotz, L.G. Lee. 2010. Synoptic classification of snowfall events in the Great Smoky Mountains, USA. *Physical Geography* 31: 156-171.

Perry, L.B., A. Seimon, G.M. Kelly. 2013. Precipitation delivery in the tropical high Andes of southern Peru: New findings and paleoclimatic implications. *International Journal of Climatology*, in press. DOI: 10.1002/joc.3679

Peters, G., B. Fischer, T. Andersson, 2002. Rain observations with a vertically looking Micro Rain Radar (MRR). *Boreal Environment Research* **7**: 353–362.

Rasmussen, R., and co-authors. 2012. How well are we measuring snow? The NOAA/FAA/NCAR winter precipitation test bed. *Bulletin of the American Meteorological Society* 93: 811-829.

Sugg, J.W., L.B. Perry, D.K. Hall. 2012. Satellite and surface perspectives of snow extent in the Southern Appalachian Mountains. *Proceedings of the 69th Eastern Snow Conference*, 21-38.

Yuter, S.E., D.A. Stark, M.T. Bryant, B.A. Colle, L.B. Perry, J. Blaes, J. Wolfe, and G. Peters, 2008. Forecasting and characterization of mixed precipitation events using the MicroRainRadar. *Proceedings of the Fifth European Conference on Radar Meteorology and Hydrology.*

Yuter, S. E., and R. A. Houze Jr. 2003. Microphysical modes of precipitation growth determined by vertically pointing radar in orographic precipitation during MAP. *Quarterly Journal of the Royal Meteorological Society* 129**,** 455–476.